The composition of transiting giant extrasolar planets.

T Guillot

Laboratoire Cassiopée, CNRS UMR 6202, Observatoire de la Côte d'Azur, BP4229, 06304 Nice Cedex 4

E-mail: guillot@obs-nice.fr

Abstract. In principle, the combined measurements of the mass and radius a giant exoplanet allow one to determine the relative fraction of hydrogen and helium and of heavy elements in the planet. However, uncertainties on the underlying physics imply that some known transiting planets appear anomalously large, and this generally prevent any firm conclusion when a planet is considered on an individual basis. On the basis of a sample of 9 transiting planets known at the time, Guillot et al. *A&A* **453**, L21 (1996), concluded that all planets could be explained with the same set of hypotheses, either by large but plausible modifications of the equations of state, opacities, or by the addition of an energy source, probably related to the dissipation of kinetic energy by tides. On this basis, they concluded that the amount of heavy elements in close-in giant planets is correlated with the metallicity of the parent star. Furthermore they showed that planets around metal-rich stars can possess large amounts of heavy elements, up to 100 Earth masses. These results are confirmed by studying the present sample of 18 transiting planets with masses between that of Saturn and twice the mass of Jupiter.

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1. Introduction

The discovery of exoplanets in transit in front of their parent star has led to the birth of a new field in science: exoplanetology, defined as the study of the characteristics, formation and fate of planets outside our solar system. I will not venture into trying to detail the possibility offered by these transiting systems, but they are numerous. One will be of importance for us, the possibility to measure relatively precisely both the mass and radius of these planets and thus armed with theoretical models, to constrain their compositions.

The first transiting exoplanet detected, HD209458b (Charbonneau et al. 2000, Henry et al. 2000), was shown to have a radius of $1.35\,\mathrm{R_J}$ for a mass of $0.65\,\mathrm{M_J}$ ($\mathrm{R_J}$ = 71492km is Jupiter's equatorial radius at 1 bar, and $\mathrm{M_J}$ is Jupiter's mass). This large radius implied naturally that the planet was a gas giant, mainly formed with hydrogen and helium (Guillot et al. 1996, Burrows et al. 2000), and a sign that our

understanding of planet formation, badly shaken by the discovery of 51 Peg b, was not completely off-track.

However, HD209458b was then shown to be anomalously large (Bodenheimer et al. 2001, Guillot & Showman 2002), i.e. larger than predicted by the evolution of a solar composition gas with no addition of any heavy elements. In contrast, when other transiting planets were found, they appeared to be "normal" within the error bars (Baraffe et al. 2005, Laughlin et al. 2005), although some indications that they could possess relatively large amounts of heavy elements were found (Guillot 2005). This is until HD149026b was shown to be significantly smaller than expected, requiring the presence of a large amount $\sim 70\mathrm{M}_\oplus$ of heavy elements in its interior (Sato et al. 2005, Fortney et al. 2006).

On the basis of the 9 transiting planets known at the time, Guillot et al. (2006) proposed to explain the structure of all planets with the same hypotheses. This required two elements: invoking a "missing physics" (e.g. energy dissipation, a modification of equations of state or opacities), with the same rules for every planet, and allowing for a variable amount of heavy elements in their interior. Their results indicated a likely correlation between the mass of heavy elements in the planets and the metallicity of the parent star. This was later confirmed by Burrows et al. (2007), on the basis of a sample that had grown to 14 members, and using as "missing physics" an increased opacity to slow the contraction of the planets.

This paper updates and extends the previous work by considering a sample of 18 planets. I purposely leave out two transiting planets with masses that are quite far from the Saturn-Jupiter mass range: GJ436 (Gillon et al. 2007), a $\sim 20\mathrm{M}_\oplus$ planet, and HD147506 (aka HAT-P-2) (Bakos et al. 2007), with its $8.2\,\mathrm{M_J}$ mass. Other planets are shown in table 1. Section 2 describes the principle of the calculations. I then show on the basis of standard evolution calculations that anomalously large planets are common, with strong implications for which mechanisms can be responsible for the slowing of the contraction. Section 4 examines several hypotheses for the "missing physics" and investigates the mass of heavy elements - stellar metallicity correlation.

2. Principle and hypotheses of the calculations

Once they have formed, giant planets contract monotonically and quasi-statically. The model used to calculate their evolution is described elsewhere (see Guillot 2005). It assumes that the planets are made of a central core which contributes relatively little to the global cooling, and of an extended, solar-composition envelope which accounts for most of the planetary size and internal energy.

An important problem behind models of the physical evolution of giant planets lies in the initial condition used and in their orbital evolution. Fortunately, initially extended planets cool and contract rapidly when the stellar irradiation is not dominant, so that initial conditions are generally forgotten over timescales of 10^7 to 10^8 years (see Marley et al. 2007). The situation may be more complex for Pegasids because of

Table 1. Transiting planets included in this study

Name	Age [Ga]	[Fe/H]	$T_{\mathrm{eq},0}$ [K]	M_{p} [$\mathrm{M_J}$]	R_{p} [$\mathrm{R_J}$]	Refs.
HD209458	4 – 7	0.02(3)	1469(120)	0.69(20)	1.320(25)	[Ch00]Wi05/Kn07
OGLE-TR-56	2 – 4	0.25(8)	2214(72)	1.29(12)	1.300(50)	[Ko03]To04/Po07
OGLE-TR-113	0.7 – 10	0.15(10)	1340(80)	1.35(22)	1.090(30)	[Bo04]Gi06
OGLE-TR-132	0.5 – 2	0.37(7)	2110(100)	1.19(13)	1.180(70)	[Bo04]Gi07
OGLE-TR-111	1.1 – 10	0.19(7)	1033(36)	0.52(13)	1.010(40)	[Po04]Sa06/Wi07/Mi07
OGLE-TR-10	1.1 – 5	0.28(10)	1509(80)	0.61(13)	1.122(100)	[Ko05]Po07/Ho07
TrES-1	2 – 6	0.06(5)	1156(140)	0.75(7)	1.081(29)	[Al04]So04/Wi07
HD149026	1.2 – 2.8	0.36(5)	1740(150)	0.33(3)	0.726(64)	[Sa05]Ch06
HD189733	0.5 – 10	−0.03(4)	1199(100)	1.15(4)	1.154(32)	[Bo05]Po07
XO-1	0.65 – 8	0.015(40)	1255(100)	0.90(7)	1.184(25)	[Mc06]Ho06/M06
HAT-P-1	2.6 – 4.6	0.13(2)	1316(61)	0.53(4)	1.203(51)	[Ba07]Wi07
TrES-2	2.8 – 7.8	−0.15(10)	1459(90)	1.28(9)	1.220(45)	[OD06]So07
WASP-1	0.3 – 3	0.26(3)	1849(80)	0.867(73)	1.443(89)	[Ca06]Sh06/Ch06
WASP-2	0.3 – 10	?	1293(136)	0.88(7)	1.038(50)	[Ca06]Ch06
XO-2	1 – 3	0.45(2)	1316(21)	0.57(6)	0.973(30)	[Bu07]
TrES-3	0.3 – 10	?	1644(90)	1.92(23)	1.295(81)	[OD07]
TrES-4	0.3 – 10	?	1757(89)	0.84(20)	1.674(94)	[Ma07]
HAT-P-3	0.3 – 10	0.27(4)	1150(38)	0.599(26)	0.890(46)	[To07]
HAT-P-4	3.6 – 6.8	0.24(8)	1689(60)	0.680(40)	1.270(50)	[Ko07]

The numbers in parenthesis represent the uncertainties on the corresponding last digits. $\mathrm{M_{Jup}} = 1.8986112 \times 10^{30}$ g is the mass of Jupiter. $\mathrm{R_{Jup}} = 71,492$ km is Jupiter's equatorial radius.

References: (Charbonneau et al. 2000, Konacki et al. 2003, Bouchy et al. 2004, Pont et al. 2004, Torres et al. 2004, Alonso et al. 2004, Sozzetti et al. 2004, Sato et al. 2005, Bouchy et al. 2005, Winn et al. 2005, O'Donovan et al. 2006, Collier Cameron et al. 2006, Knutson et al. 2007, Gillon et al. 2006, Charbonneau et al. 2006, Holman et al. 2006, Shporer et al. 2007, Winn, Holman & Fuentes 2007, Winn, Holman & Roussanova 2007, Bakos et al. 2007, Burke et al. 2007, O'Donovan et al. 2007, Mandushev et al. 2007, Torres et al. 2007, Pont et al. 2007, Gillon et al. 2007, Minniti et al. 2007, Winn, Holman & Fuentes 2007, Kovacs et al. 2007); The discovery papers are in brackets. The table is taken from F. Pont's site: `http://obswww.unige.ch/~pont/TRANSITS.htm`.

their rather slow initial contraction (Guillot et al. 1996), and the possibility that they may have formed at larger distances before being brought close to their stars (Burrows et al. 2000).

To make things simple, I assume that all planets have an initial radius of $2\,\mathrm{R_J}$, have formed in situ, and underwent a constant irradiation from their parent star. Although this hypothesis can certainly be questioned, it has a limited impact on the results (e.g. Ikoma et al. 2006). Most importantly, applying the same set of hypotheses consistently to all the transiting planets considered will eventually enable testing them when a statistically sufficient number of such planets will have been discovered.

The assumption of solar composition in the envelope may also be surprising in regard to the fact that our giant planets appear to all be significantly enriched (by

factors of ~ 3 for Jupiter to 30 for Uranus and Neptune over the Solar value). At this point, this is a clear simplification, to be further discussed in § 4.2.

Important ingredients entering the calculations are the equations of state. The well-known EOS by Saumon et al. (1995) is used in the envelope. This EOS includes only hydrogen and helium, but a slightly larger mass fraction of helium ($Y = 0.30$) is used to mimic the presence of a solar composition of heavy elements. The dense core is assumed to be made of pure rocks, and the EOS is based on the experimental fit by Hubbard & Marley (1989). Unless otherwise stated, the mass of the core is the only parameter to be modified in the calculations.

The opacities are based on a table calculated by Allard et al. (2001). These opacities do not account for the possible presence of clouds. The progressive growth of an external radiative zone governs most of the evolution (in particular contraction) of irradiated giant planets (Guillot et al. 1996). I will come back on how modifications to the opacities can change the analysis of the compositions of Pegasids.

The atmospheric boundary condition used in these calculations is simplified. In the case of the first 9 transiting planets, I use specific atmospheric models calculated on the basis of Iro et al. (2005). For the remaining planets, a simple relation is used:

$$T_{10} = 1.25 T_{\rm eq,0}, \tag{1}$$

where T_{10} is the temperature at the 10 bar level, and $T_{\rm eq,0}$ is the equilibrium temperature at the planet for a $A = 0$ albedo (perfect absorption). Figure 1 shows how this approximate relation compares to the more elaborate but 1D radiative transfer calculations.

The difference between the observed transit radius (at $\sim$mbar levels) and the modelled radius (at 10 bar) has to be taken into account (see Burrows et al. 2003). As in Guillot et al. (2006), we include this radius difference as:

$$\Delta R = \frac{\mathcal{R} T_{\rm eq,0}}{\mu g} \ln\left(\frac{P_{\rm model}}{P_{\rm transit}}\right), \tag{2}$$

where $P_{\rm model} = 10\,$bar, we assume $P_{\rm transit} = 1\,$mbar, $\mathcal{R}$ is the gas constant, μ is the mean molecular weight (we use $\mu = 2.2$) and g is the atmospheric gravity. This relation uses a mean atmospheric temperature equal to $T_{\rm eq,0}$. Clearly eq. 2 is an approximation, both from the point of view of the transit pressure, and from that of the atmospheric temperature structure. However, what is most important is that whatever the error made here, it applies to *all planets in the same way*. Furthermore, I claim that it is small compared to the inherent uncertainties related to atmospheric models (including the possible presence of clouds and their structure, the inhomogeneous heating and the resulting dynamical effects).

3. Anomalously large planets are common!

Figure 2 shows the masses of heavy elements that are needed to explain the observed radius measurements, using a standard evolution model. The results are plotted as a

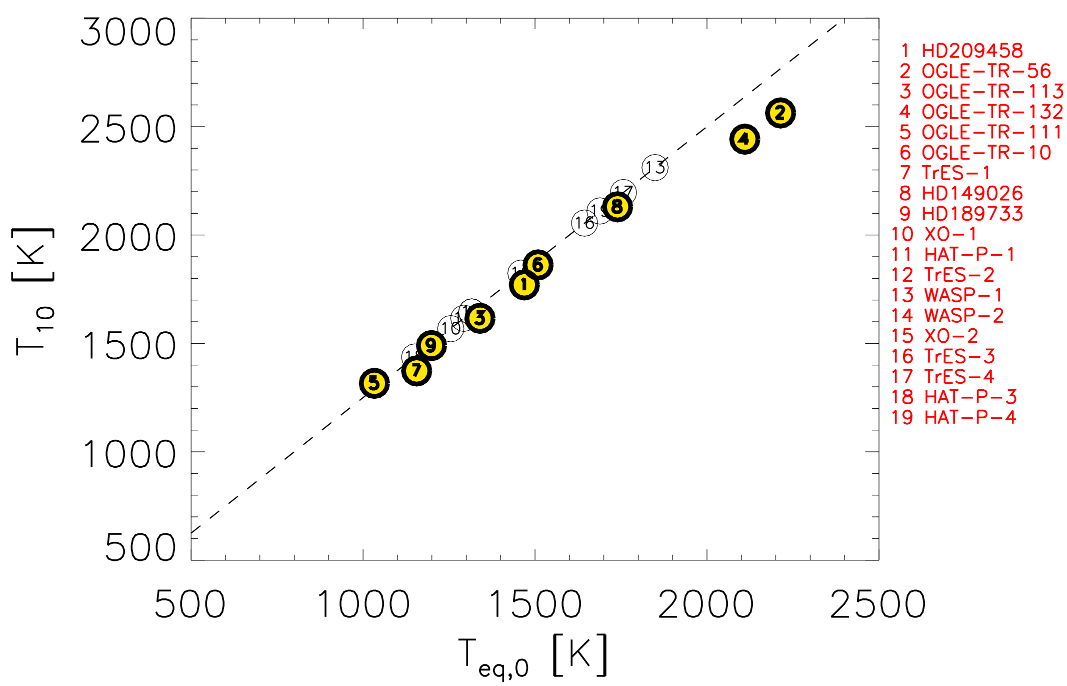

Figure 1. Temperature at the 10 bar level as a function of the equilibrium temperature, as calculated with a 1D equilibrium model (Iro et al. 2005) (cases 1 to 9) and when assuming $T_{10} = 1.25 T_{\rm eq,0}$ (cases 10 to 18).

function of the heavy element enrichment in the parent star (i.e. $10^{[\rm Fe/H]}$, where [Fe/H] is the metallicity).

As already observed by many authors (Bodenheimer et al. 2001, Guillot & Showman 2002, Chabrier et al. 2004), HD209458b is anomalously large. In figure 2, this implies that the planet appears with a *negative* core mass‡, which is of course physically impossible. Of interest to us is the fact that a rather large number of planets (HD209458b, TrES-2b, WASP-1b, TrES-3b, TrES-4b, HAT-P-4b, and probably also OGLE-TR-56b, HD189733b, XO-1b, HAT-P-1b), 6 to 10 over 19, appear in the negative core mass side of the diagram.

Clearly, this rules out mecanisms that are statistically unlikely as responsible of the large radii. The small but non-zero eccentricity explanation (Bodenheimer et al. 2001) is already excluded for HD209458b (Deming et al. 2005, Laughlin et al. 2005). The spin-orbit trapping into a Cassini state (Winn & Holman 2005), has been shown to be unprobable (Levrard et al. 2007, Fabrycky et al. 2007). On the other hand, the semi-convection mechanism put forward by Chabrier & Baraffe (2007) cannot be ruled out, but one would expect it to work more efficiently at large metallicities, which seems not

‡ Note that I did not attempt to calculate hydrostatic models using negative core masses: this is a result of the interpolation (in this case extrapolation) technique used to obtain the core mass. As a result, the precise value of M_Z is of little significance when negative.

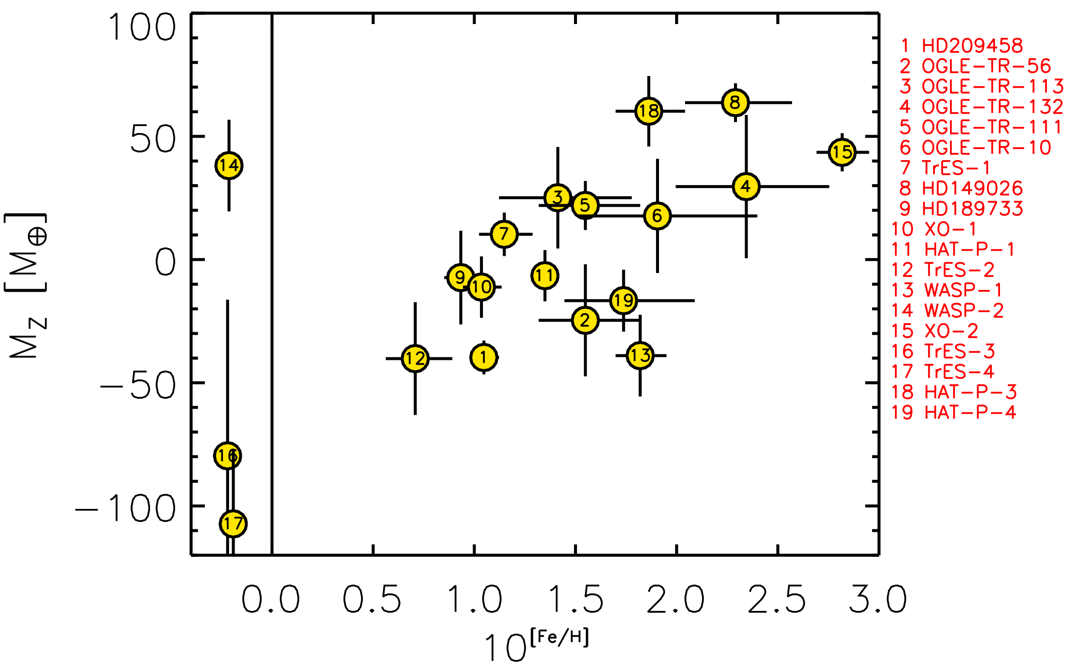

Figure 2. Mass of heavy elements in the planets as a function of the metal content of the parent star relative to the Sun. The mass of heavy elements required to fit the measured radii is calculated on the basis of standard evolution models. Negative core masses are required in some cases, implying that some significant physical input is missing (see text). Horizontal error bars correspond to the 1σ errors on the [Fe/H] determination. Vertical error bars are a consequence of the uncertainties on the measured planetary radii and ages.

to be compatible with the results of fig 2.

Altogether, this strengthens the case of a mechanism at work for *all* planets, as discussed in previous papers (Guillot 2005, Guillot et al. 2006). The rest of the article will be based on this assumption: whatever happens to HD209458b or TrES-4b must also be occuring for all other pegasids.

4. Explaining the observations

4.1. A hard equation of state model

A first possibility is that the hydrogen helium equation of state (EOS) used is not quite right and overestimates the density for a given pressure, temperature and composition (we need hydrogen to be "harder", i.e. less compressible). Rather large uncertainties ($\sim 10-20\%$) of the density predicted by different equations of state are possible at pressures and temperatures relevant to giant planet interiors (Saumon & Guillot 2004). A 30% *softening* of the hydrogen EOS compared to the SCVH EOS has been obtained

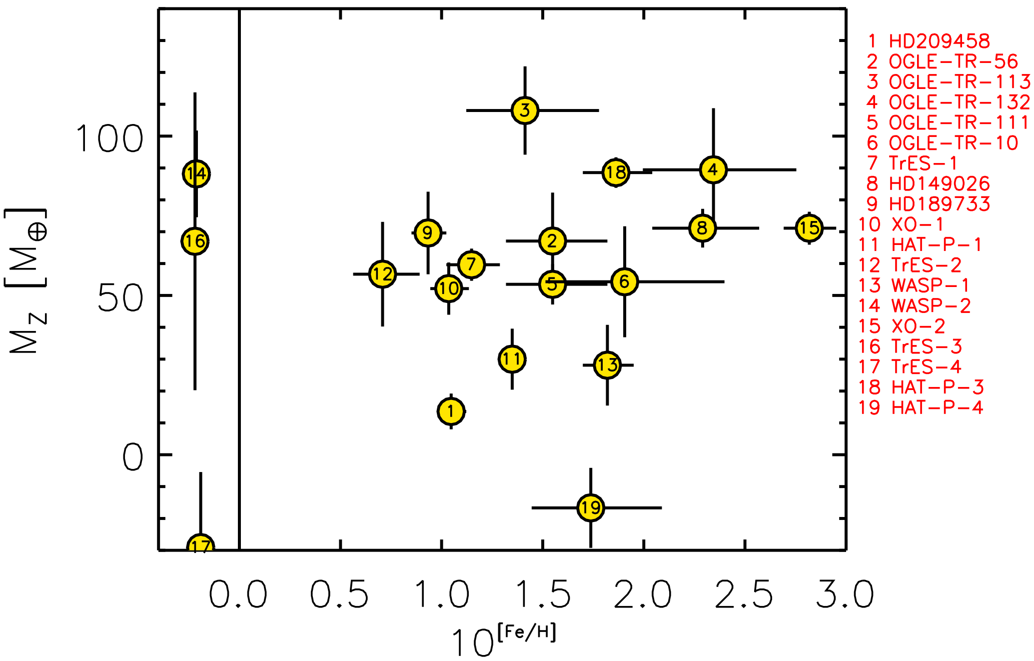

Figure 3. Same as fig. 2, but the mass of heavy elements required to fit the measured radii are calculated on the basis of evolution models of a planet with no helium, to mimic a hard hydrogen EOS (see text).

as a result of ab-initio simulations matching high-pressure experiments (Militzer & Hubbard, personnal communication; see also Militzer et al. (2006)). Although this last result goes in the wrong direction for us, it shows that the EOS is an important uncertainty source.

In order to test the possibility that the EOS may be the culprit in the underestimations of theoretical planetary radii, I present in fig. 3 models calculated with the SCVH EOS, but with helium removed. This is similar in essence to a $\sim 30\%$ hardening of the EOS.

As a result, we find that this large change to the EOS is sufficient to explain the present radii of all planets except TrES-4b and HAT-P-4b. However, these two planets have been discovered recently, and still have relatively large error bars. Future measurements are needed for these objects.

Globally, the trend between M_Z and [Fe/H] that was seen in the standard model is mostly lost: this effect is an artificial one that is related to the different adiabats of hydrogen and helium. As a result, the change in radius between a pure H planet and a H/He mixture is greater for planets that receive less flux from their star. It shows however that both changes in the density and specific entropies have to be carefully accounted for in new EOSs.

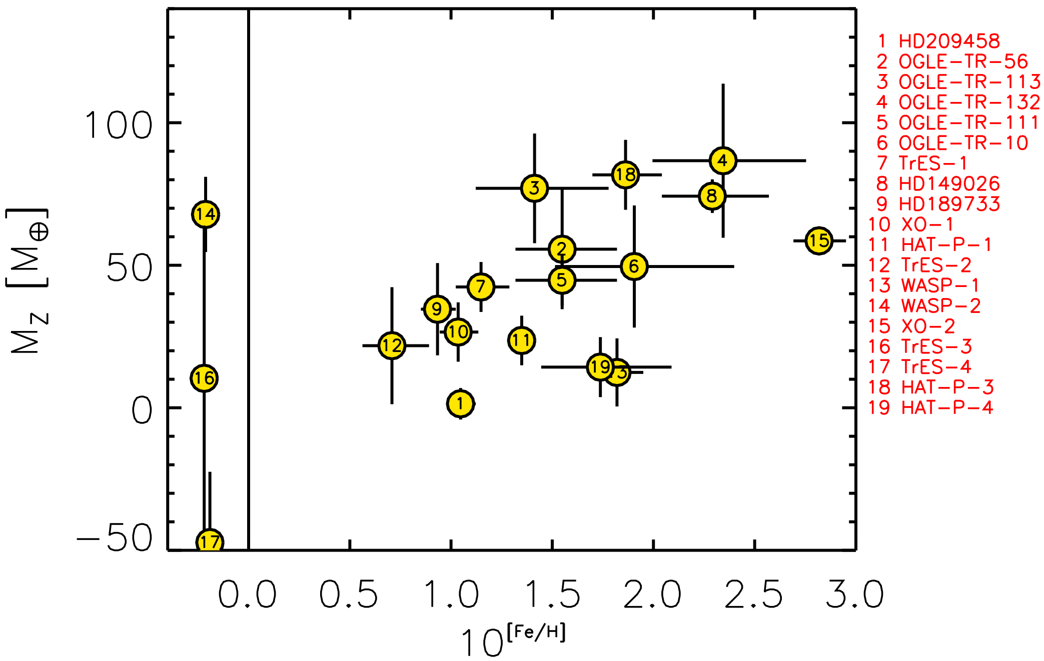

Figure 4. Same as fig. 2, but the mass of heavy elements required to fit the measured radii are calculated on the basis of evolution models with opacities arbitrarily increased by a factor 30.

4.2. An increased opacity scenario

Another possibility to explain the anomalously large planets is a serious underestimation of the Rosseland opacities. The growth of the external radiative region (down to ∼kbar pressure levels) controls the cooling and hence the contraction of all pegasids (Guillot et al. 1996, Guillot & Showman 2002). This region is in a difficult, relatively cold but dense region, and generally, opacities are notoriously famous for the large uncertainties associated to them.

Figure 4 presents results obtained with Rosseland opacities that have been arbitrarily multiplied by a factor 30 compared to the fiducial values. This value corresponds approximatively to the increase that is needed to explain the radius measured for HD209458b.

It can be seen that this approach leads to physically sound values of the heavy element masses for all planets, with two exceptions: TrES-4b and HAT-P-3b. It may be premature however to rule out this explanation because these discoveries are quite recent, and experience has shown that the inferred radii which are very dependent on stellar properties have often moved a bit more than would be expected from their $1-\sigma$ error bar. It is clear that TrES-4b and HAT-P-3b are extremely interesting planets to test these models. More discoveries will of course also help to settle the matter.

Interestingly, we again observe a clear correlation between planetary and stellar "metallicity". This result, first found by Guillot et al. (2006), was later confirmed by Burrows et al. (2007). A preliminary version of the last paper, put onto astro-ph, claimed that this opacity increase was related to an oversolar enrichement of the envelope, a simple, logical explanation when considering that the atmospheres of our giant planets are enriched in heavy elements. However this explanation was based on a model for which only opacities had been increased, and not the mean molecular weight. A consistent treatment, unfortunately, rules out this simple explanation as a solution to the anomalously large planets problem.

The reason for that is a balancing effect between the slower cooling and the increased mean molecular weight that implies that enriching the envelopes in heavy elements does not generally make the planets larger, and often results in the oposite effect. Figure 5 shows that the mean molecular weight effect eventually wins, and that this occurs over a timescale similar to the ages of the systems that are observed.

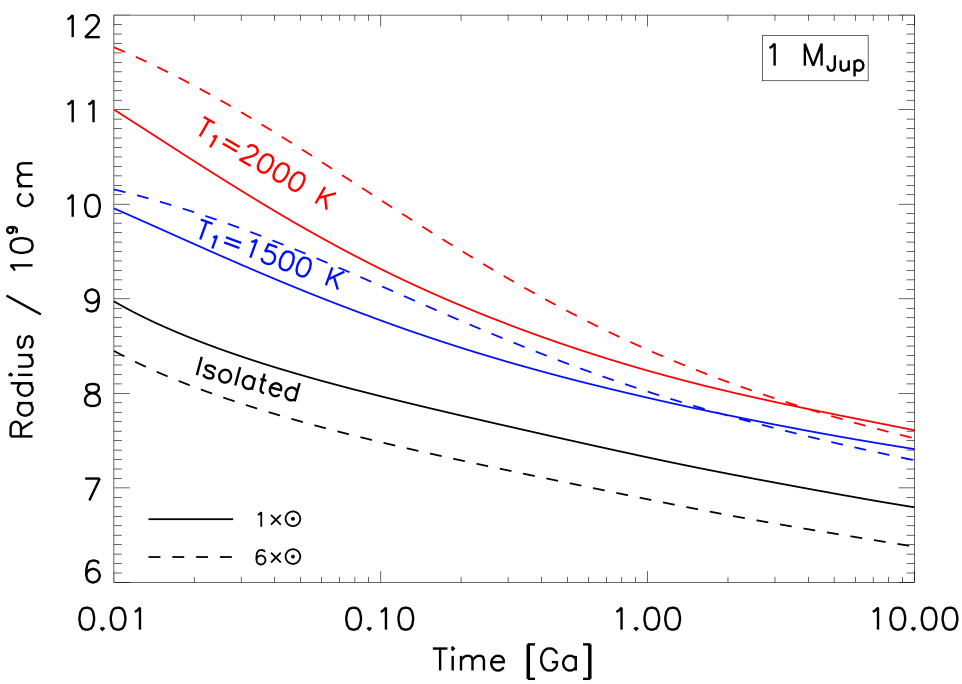

Figure 5. Evolution of giant planets in terms of radius vs. time, for different irradiation levels, and 2 assumed compositions: solar, and 6 times solar. (This calculation ignores second order effects as modifications of the adiabatic temperature gradient and non-linear effects in the opacity calculation, and more importantly modifications of atmospheric properties.) [From Guillot (2005)].

Could the atmosphere or the upper part of the envelope be enriched in heavy elements while the rest would not? This is regarded as extremely unlikely, because a double-diffusive instability ("salt-fingers") should set in (e.g. Stevenson 1985).

Finally, there is an interesting possibility that the envelopes of giant planets orbiting metal-rich stars are more enriched than for planets orbiting metal-poor stars. This case would lead to a *stronger* correlation between heavy elements in the planet and stellar metallicity.

4.3. The kinetic energy mechanism

The third mechansim that would be in action for all the planets, but at a level that depends on the irradiation that they receive from the parent star is the one proposed by Showman & Guillot (2002): a fraction ($\sim 1\%$) of the energy recieved in form of stellar irradiation by the planet is converted into kinetic energy in the atmosphere. This energy is transported to deeper levels, and dissipated probably due to tidal interactions with the star. Although simulations and observations on Earth have shown this amount of kinetic energy to be generated in the atmosphere, several problems remain with this scenario: first the turbulent viscosity needs to be small otherwise dissipation takes place in the upper atmosphere, with little effect on the planet's contraction (Burkert et al. 2005); Second kinetic energy must be transported to the 10-100bar level at least; Third, it must be dissipated there (or at deeper levels).

Figure 6 shows results obtained with this model, assuming a 0.5% dissipation of the incoming stellar flux at the center of the planet. This level of dissipation is chosen so as to yield a small but positive value for the mass of heavy elements inside HD209458b. (Larger values lead to systematically larger masses of heavy elements derived in all transiting planets.) As previously mentioned (Guillot et al. 2006), the relation between the mass of heavy elements in the planet and the stellar metallicity is qualitatively similar than when increasing opacities.

5. Conclusions

With the 18 transiting exoplanets with masses between that of Saturn and twice the mass of Jupiter known thus far, we are able to confirm the conclusions derived by Guillot et al. (2006):

- All planets can be explained in the framework of a single scenario, when accounting for some missing physics which can either be due to modifications in the EOSs, opacities, or to an additional heating source.
- Giant planets can possess a large mass in heavy elements, up to 100 Earth masses (a value which is itself model-dependent).
- There is a correlation between the mass of heavy elements in the planets and the metallicity of their parent stars, so that the most massive planets generally orbit the most massive stars. This correlation is probably *not* a single relation, but shows, as would be expected, some scatter. However, there is presently an *absence* of planets with small masses of heavy elements around metal-rich stars, planets that appear to be predicted by formation models (see Alibert et al. 2005).

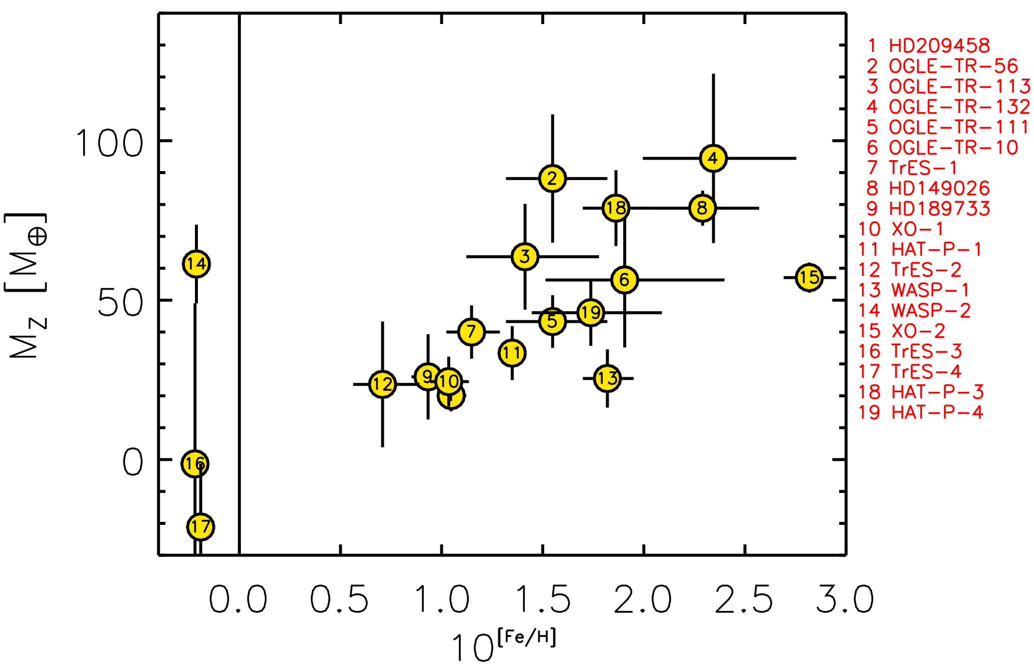

Figure 6. Same as fig. 2, but the mass of heavy elements required to fit the measured radii are calculated on the basis of evolution models including an additional heat source slowing the cooling of the planet. This heat source is assumed equal to 0.5% of the incoming stellar heat flux (Showman & Guillot 2002).

- Planets around stars that have metallicities comparable to that of our Sun generally tend to have very small cores. There is a clear lack of giant planets at short periods ($P < 10$ days) around metal-poor stars (Fressin et al. 2007). This seems to imply that metal-poor stars are not able to form giant planets and have them migrate very close-in.

It should be noted however that a planet such as TrES-4 may pose a problem for these models if its large radius is confirmed. It is presently too large to be explained by the models, but the error bars are currently quite large and prevent any definitive conclusion to be made. Future detections of both large and small transiting pegasids are extremely important to test the models and better understand how giant planets formed.

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References

Alibert Y, Mordasini C, Benz W & Winisdoerffer C 2005 *A&A* **434**, 343–353.

Allard F, Hauschildt P H, Alexander D R, Tamanai A & Schweitzer A 2001 *ApJ* **556**, 357–372.

Alonso R, Brown T M, Torres G, Latham D W, Sozzetti A, Mandushev G, Belmonte J A, Charbonneau D, Deeg H J, Dunham E W, O'Donovan F T & Stefanik R P 2004 *ApJ* **613**, L153–L156.

Bakos G A, Kovacs G, Torres G, Fischer D A, Latham D W, Noyes R W, Sasselov D D, Mazeh T, Shporer A, Butler R P, Stefanik R P, Fernandez J M, Sozzetti A, Pal A, Johnson J, Marcy G W, Winn J, Sipocz B, Lazar J, Papp I & Sari P 2007 *ArXiv e-prints* **705**.

Bakos G Á, Noyes R W, Kovács G, Latham D W, Sasselov D D, Torres G, Fischer D A, Stefanik R P, Sato B, Johnson J A, Pál A, Marcy G W, Butler R P, Esquerdo G A, Stanek K Z, Lázár J, Papp I, Sári P & Sipőcz B 2007 *ApJ* **656**, 552–559.

Baraffe I, Chabrier G, Barman T S, Selsis F, Allard F & Hauschildt P H 2005 *A&A* **436**, L47–L51.

Bodenheimer P, Lin D N C & Mardling R A 2001 *ApJ* **548**, 466–472.

Bouchy F, Pont F, Melo C, Santos N C, Mayor M, Queloz D & Udry S 2005 *A&A* **431**, 1105–1121.

Bouchy F, Pont F, Santos N C, Melo C, Mayor M, Queloz D & Udry S 2004 *A&A* **421**, L13–L16.

Burke C J, McCullough P R, Valenti J A, Johns-Krull C M, Janes K A, Heasley J N, Summers F J, Stys J E, Bissinger R, Fleenor M L, Foote C N, Garcia-Melendo E, Gary B L, Howell P J, Mallia F, Masi G, Taylor B & Vanmunster T 2007 *ArXiv e-prints* **705**.

Burkert A, Lin D N C, Bodenheimer P H, Jones C A & Yorke H W 2005 *ApJ* **618**, 512–523.

Burrows A, Guillot T, Hubbard W B, Marley M S, Saumon D, Lunine J I & Sudarsky D 2000 *ApJ* **534**, L97–L100.

Burrows A, Hubeny I, Budaj J & Hubbard W B 2007 *ApJ* **661**, 502–514.

Burrows A, Sudarsky D & Hubbard W B 2003 *ApJ* **594**, 545–551.

Chabrier G & Baraffe I 2007 *ApJ* **661**, L81–L84.

Chabrier G, Barman T, Baraffe I, Allard F & Hauschildt P H 2004 *ApJ* **603**, L53–L56.

Charbonneau D, Brown T M, Latham D W & Mayor M 2000 *ApJ* **529**, L45–L48.

Charbonneau D, Winn J N, Latham D W, Bakos G, Falco E E, Holman M J, Noyes R W, Csák B, Esquerdo G A, Everett M E & O'Donovan F T 2006 *ApJ* **636**, 445–452.

Collier Cameron A, Bouchy F, Hebrard G, Maxted P, Pollacco D, Pont F, Skillen I, Smalley B, Street R A, West R G, Wilson D M, Aigrain S, Christian D J, Clarkson W I, Enoch B, Evans A, Fitzsimmons A, Fleenor M, Gillon M, Haswell C A, Hebb L, Hellier C, Hodgkin S T, Horne K, Irwin J, Kane S R, Keenan F P, Loeillet B, Lister T A, Mayor M, Moutou C, Norton A J, Osborne J, Parley N, Queloz D, Ryans R, Triaud A H M J, Udry S & Wheatley P J 2006 *ArXiv Astrophysics e-prints* .

Deming D, Seager S, Richardson L J & Harrington J 2005 *Nature* **434**, 740–743.

Fabrycky D C, Johnson E T & Goodman J 2007 *ApJ* **665**, 754–766.

Fortney J J, Saumon D, Marley M S, Lodders K & Freedman R S 2006 *ApJ* **642**, 495–504.

Fressin F, Guillot T, Morello V & Pont F 2007 *ArXiv e-prints* . in press [astro-ph/2007arXiv0704.1919F].

Gillon M, Pont F, Demory B O, Mallmann F, Mayor M, Mazeh T, Queloz D, Shporer A, Udry S & Vuissoz C 2007 *A&A* **472**, L13–L16.

Gillon M, Pont F, Moutou C, Bouchy F, Courbin F, Sohy S & Magain P 2006 *A&A* **459**, 249–255.

Gillon M, Pont F, Moutou C, Santos N C, Bouchy F, Hartman J D, Mayor M, Melo C, Queloz D, Udry S & Magain P 2007 *A&A* **466**, 743–748.

Guillot T 2005 *Annual Review of Earth and Planetary Sciences* **33**, 493–530.

Guillot T, Burrows A, Hubbard W B, Lunine J I & Saumon D 1996 *ApJ* **459**, L35–L39.

Guillot T, Santos N C, Pont F, Iro N, Melo C & Ribas I 2006 *A&A* **453**, L21–L24.

Guillot T & Showman A P 2002 *A&A* **385**, 156–165.

Henry G W, Marcy G W, Butler R P & Vogt S S 2000 *ApJ* **529**, L41–L44.

Holman M J, Winn J N, Latham D W, O'Donovan F T, Charbonneau D, Bakos G A, Esquerdo G A,

Hergenrother C, Everett M E & Pál A 2006 *ApJ* **652**, 1715–1723.
Hubbard W B & Marley M S 1989 *Icarus* **78**, 102–118.
Ikoma M, Guillot T, Genda H, Tanigawa T & Ida S 2006 *ApJ* **650**, 1150–1159.
Iro N, Bézard B & Guillot T 2005 *A&A* **436**, 719–727.
Knutson H A, Charbonneau D, Noyes R W, Brown T M & Gilliland R L 2007 *ApJ* **655**, 564–575.
Konacki M, Sasselov D D, Torres G, Jha S & Kulkarni S R 2003 *in* 'Bulletin of the American Astronomical Society' pp. 1416–+.
Kovacs G, Bakos G A, Torres G, Sozzetti A, Latham D W, Noyes R W, Butler R P, Marcy G W, Fischer D A, Fernandez J M, Esquerdo G, Sasselov D D, Stefanik R P, Pal A, Lazar J, Papp I & Sari P 2007 *ArXiv e-prints* **710**.
Laughlin G, Marcy G W, Vogt S S, Fischer D A & Butler R P 2005 *ApJ* **629**, L121–L124.
Laughlin G, Wolf A, Vanmunster T, Bodenheimer P, Fischer D, Marcy G, Butler P & Vogt S 2005 *ApJ* **621**, 1072–1078.
Levrard B, Correia A C M, Chabrier G, Baraffe I, Selsis F & Laskar J 2007 *A&A* **462**, L5–L8.
Mandushev G, O'Donovan F T, Charbonneau D, Torres G, Latham D W, Bakos G Á, Dunham E W, Sozzetti A, Fernández J M, Esquerdo G A, Everett M E, Brown T M, Rabus M, Belmonte J A & Hillenbrand L A 2007 *ApJ* **667**, L195–L198.
Marley M S, Fortney J J, Hubickyj O, Bodenheimer P & Lissauer J J 2007 *ApJ* **655**, 541–549.
Militzer B, Vorberger J & Hubbard W 2006 *AGU Fall Meeting Abstracts* pp. A3+.
Minniti D, Fernández J M, Díaz R F, Udalski A, Pietrzynski G, Gieren W, Rojo P, Ruíz M T & Zoccali M 2007 *ApJ* **660**, 858–862.
O'Donovan F T, Charbonneau D, Bakos G Á, Mandushev G, Dunham E W, Brown T M, Latham D W, Torres G, Sozzetti A, Kovács G, Everett M E, Baliber N, Hidas M G, Esquerdo G A, Rabus M, Deeg H J, Belmonte J A, Hillenbrand L A & Stefanik R P 2007 *ApJ* **663**, L37–L40.
O'Donovan F T, Charbonneau D, Mandushev G, Dunham E W, Latham D W, Torres G, Sozzetti A, Brown T M, Trauger J T, Belmonte J A, Rabus M, Almenara J M, Alonso R, Deeg H J, Esquerdo G A, Falco E E, Hillenbrand L A, Roussanova A, Stefanik R P & Winn J N 2006 *ApJ* **651**, L61–L64.
Pont F, Bouchy F, Queloz D, Santos N C, Melo C, Mayor M & Udry S 2004 *A&A* **426**, L15–L18.
Pont F, Moutou C, Gillon M, Udalski A, Bouchy F, Fernandes J M, Gieren W, Mayor M, Mazeh T, Minniti D, Melo C, Naef D, Pietrzynski G, Queloz D, Ruiz M T, Santos N C & Udry S 2007 *A&A* **465**, 1069–1074.
Sato B, Fischer D A, Henry G W, Laughlin G, Butler R P, Marcy G W, Vogt S S, Bodenheimer P, Ida S, Toyota E, Wolf A, Valenti J A, Boyd L J, Johnson J A, Wright J T, Ammons M, Robinson S, Strader J, McCarthy C, Tah K L & Minniti D 2005 *ApJ* **633**, 465–473.
Saumon D, Chabrier G & van Horn H M 1995 *ApJS* **99**, 713–+.
Saumon D & Guillot T 2004 *ApJ* **609**, 1170–1180.
Showman A P & Guillot T 2002 *A&A* **385**, 166–180.
Shporer A, Tamuz O, Zucker S & Mazeh T 2007 *MNRAS* pp. 136–+.
Sozzetti A, Yong D, Torres G, Charbonneau D, Latham D W, Allende Prieto C, Brown T M, Carney B W & Laird J B 2004 *ApJ* **616**, L167–L170.
Stevenson D J 1985 *Icarus* **62**, 4–15.
Torres G, Bakos G Á, Kovács G, Latham D W, Fernández J M, Noyes R W, Esquerdo G A, Sozzetti A, Fischer D A, Butler R P, Marcy G W, Stefanik R P, Sasselov D D, Lázár J, Papp I & Sári P 2007 *ApJ* **666**, L121–L124.
Torres G, Konacki M, Sasselov D D & Jha S 2004 *ApJ* **609**, 1071–1075.
Winn J N & Holman M J 2005 *ApJ* **628**, L159–L162.
Winn J N, Holman M J & Fuentes C I 2007 *AJ* **133**, 11–16.
Winn J N, Holman M J & Roussanova A 2007 *ApJ* **657**, 1098–1106.
Winn J N, Noyes R W, Holman M J, Charbonneau D, Ohta Y, Taruya A, Suto Y, Narita N, Turner E L, Johnson J A, Marcy G W, Butler R P & Vogt S S 2005 *ApJ* **631**, 1215–1226.